PROPOSAL COVER SHEET

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PROJECT TITLE: Direct Strength Prediction of Cold-Formed Steel Beam-Columns

TYPE OF APPLICATION: New Grant

AMOUNT REQUESTED FROM SPONSOR: $280,387

PROPOSED STARTING DATE: September 1, 2008

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DIRECT STRENGTH PREDICTION OF COLD-FORMED STEEL BEAM-COLUMNS

Solicited *proposal submitted to:*
The American Iron and Steel Institute (AISI)

Principal Investigator:
Ben Schafer
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Abstract

This proposal provides a comprehensive program of conceptual, computational, and experimental work to modernize beam-column design of cold-formed steel members and bring this new design method immediately into the AISI Specification.

The positive impacts of the proposed research are significant and worthy. *For industry*, the method provides a means to optimize sections for the actual loading they are expected to encounter resulting in lighter more efficient sections, tailored for their expected use. *For engineers*, the proposed method provides a better understanding of the relevant behavior, more transparent use of fundamental mechanics, and improved reliability. Together, these advantages allow cold-formed steel to be designed, specified, and built in a greater number of applications, with greater confidence.

Beam-column design in AISI-S100 ignores the actual state of applied stress resulting from applied axial loads and bending demands and instead employs a linear interaction equation of the resultant forces and moments. Ignoring the actual applied stress distribution can result in overly conservative predictions, sometimes to a remarkably large degree. The development of the Direct Strength Method for cold-formed steel design has opened the potential for a new generation of highly optimized cold-formed steel members designed based on fundamental mechanics and checked for all relevant limit states. The adoption of Appendix 1 in AISI-S100 was a major step forward for this new approach, but currently the method only handles isolated beams and columns and provides no means for designing beam-columns. At the heart of the Direct Strength Method is the consideration of the cross-section stability under the relevant applied stress state. *Extension of the Direct Strength Method to beam-columns is natural* and stands to provide a significant benefit to cold-formed steel design.

1. Background

The Direct Strength Method (DSM) is a robust and flexible new design method for cold-formed steel members. Through research funded by AISI, and the efforts of many members of the AISI Committee on Specification, as well as the author, DSM is now an accepted alternative design method in the AISI Specification for the Design of Cold-Formed Steel Structural Members (AISI-S100). In its adopted form (Appendix 1 of AISI-S100) DSM only applies to beams and columns. *Beam-columns, which are a fundamental building block for structures, are not currently handled by DSM*. A full discussion of the background and development of DSM is available in Schafer 2008.

Extension of the strength prediction of isolated beams and columns to the more general case of a beam-column (a member with combined axial load and bending) requires the consideration of at least two fundamental issues: *(1) amplification of bending demands*, and *(2) necessity to include interactions* in capacity. The amplification of the bending demand is due to 2nd order P-δ and P-Δ moments that occur as the axially loaded beam deflects laterally. These moments may be significant, and must be accounted for in design. Traditionally, the moment amplification has been completed by hand, employing, what is commonly referred to as the B_1, B_2 method of hot-rolled steel design. Our cold-formed steel specification usea a similar method. More recently, computational 2nd order analysis methods and strongly related notional load approaches have been explored and recently codified in AISI-S100 Appendix 2 for handling moment amplification in beam-columns. This proposal will consider and incorporate the recommendations currently being made in the structural engineering community regarding moment amplification for beam-columns*, but this work is not the focus of the proposed research.

Beam-column design requires consideration of interaction, because at its most elementary level axial loads and bending moments both create primary longitudinal stresses in a cross-section, and thus they must be checked together. In most steel codes checking for member capacity in the presence of axial loads and bending moments is handled by an interaction equation, which in its simplest form may be expressed as:

$$\frac{P_{demand}}{P_{capacity}} + \frac{M_{x-demand}}{M_{x-capacity}} + \frac{M_{y-demand}}{M_{y-capacity}} \leq 1.0 \qquad (1)$$

For a fully effective, doubly-symmetric section, with a first yield criterion for strength (i.e., $|f_{max}| = f_y$ determines capacity) then Eq. 1 is exact. For members undergoing any manner of instability: local, distortional, or global, and/or with a more general cross-section: singly-symmetric, point-symmetric, un-symmetric, etc., *Eq. 1 is a conservative, in some cases absurdly conservative, approximation*.

The behavior of a track section (unlipped channel) as a beam-column provides an illustration of the importance of analyzing a cross-section for the actual applied stress state. Interaction equations, such as Eq. 1, assume that the presence of any additional bending will decreases the capacity – since the maximum stress in the cross-section is accentuated by the bending. Instead, we have found local buckling is governed more strongly by the distribution of stress rather than the absolute maximum. For the track section of Figure 1 the elastic local buckling load is 55 kN in pure compression. As Figure 1 indicates, when the minor axis eccentricity (bending) relieves the stress on the lips the axial local buckling load actually increases substantially to 123 kN as local buckling switches from the lip to the web, even though the interaction approach would presume the buckling must occur at a load less than 55 kN. Analysis of stability for the proper applied stress is essential, in this case eccentricity can help!

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[*] Essentially this includes AISI-S100-07 Appendix 2 and AISC 2005 Appendix 7.

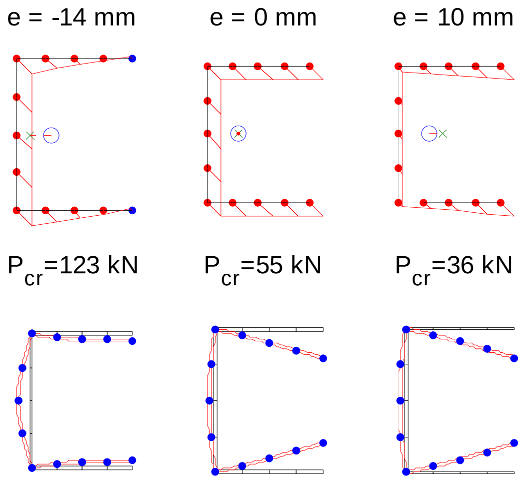


Figure 1 Local buckling of an axially loaded channel under minor axis eccentricity
(Eccentricities can actually increase the local buckling load, contrary to traditional interaction equations which always presume the eccentricity will decrease the capacity.)

As Appendix 1 describes in further detail, linear interaction equations are incorrect (but conservative) both for prediction of strength and stability. Until recently, determination of beam-column strength was generally felt to be too complex to bother with creating unique interaction equations for every cross-section (as is done for example in concrete design). Today, direct numerical determination of any unique axial + bending combination may be found using elastic buckling analysis tools such as the finite strip method (i.e., CUFSM). Readily available tools for stability under any combination of applied stresses (e.g., axial + biaxial bending) combined with Direct Strength expressions for each limit state can fundamentally change beam-column design. Overly conservative interaction equations which ignore basic mechanics can be dropped in favor of straightforward tools which explicitly consider the actual state of applied stress and the resulting stability. The development of DSM for beam-columns has the potential to provide a more mechanically sound solution to the strength of beam-columns, eliminate excessive conservativeness, and at the same time encourage a new generation of highly optimized, high strength, cold-formed steel shapes.

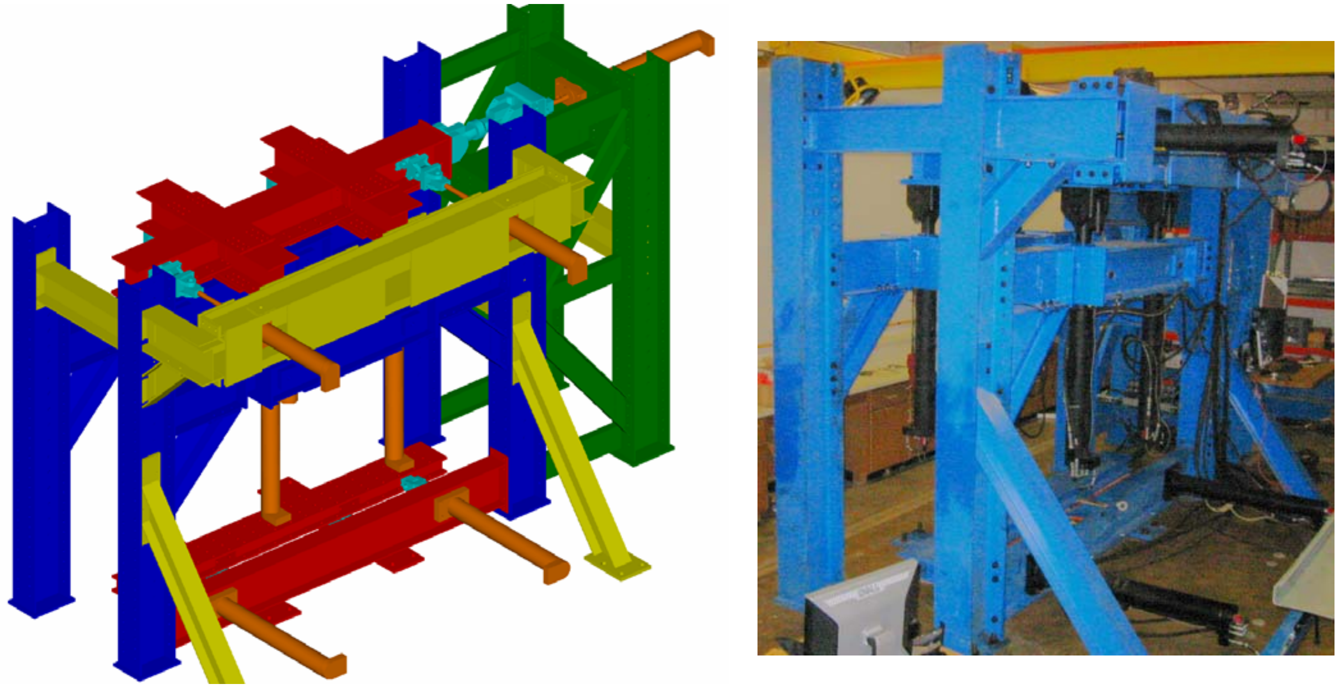
2. Statement of Work

Objective: The development and verification of a design method for beam-columns that explicitly and directly considers the applied actions, including axial loads and biaxial bending, in uniquely determining the stability and strength of a member under those actions.

Achievement of the proposed objective may be divided into 3 categories: conceptual, computational, and experimental. *The conceptual work* will develop the framework for the design method, and address theoretical difficulties associated with extending the isolated DSM strength equations for beams and columns to more general beam-column loading case including path dependence, neutral axis shift, local buckling of isolated thin parts of the section. *The computational work*, focused on nonlinear finite element analysis (FEA) modeling in ABAQUS, will support the experimental program and also be used to provide a much richer prediction of beam-column capacities failing in all potential limit states for widely varying member cross-sections and details. *The experimental work* will provide a focused effort for strength prediction of sections commonly used in industry and those which are expected to have unusual differences between current practice and actual behavior. The experimental program will provide validation and reliability predictions (ϕ, Ω) for the newly developed DSM beam-column rules.

Why we need experiments: For isolated thin-walled beams and columns enough data existed to formulate DSM rules with a reasonable level of reliability (e.g., see the summary in Peköz 1987 or Schafer 2002). However, existing data on cold-formed steel beam-columns is limited to a small series of tests on low yield stress (f_y = 228 MPa, 33 ksi) hat sections (Peköz and Winter 1969) and lipped channels (Loh and Peköz 1985) conducted at only one length for each cross-section. The work did not investigate the influence of eccentricity on individual cross-section modes such as local and distortional since flexural-torsional buckling was the primary focus. Existing data does not provide a basis for comprehensive evaluation of DSM for beam-columns.

The testing will be conducted in the multi-degree of freedom (MDOF) testing rig at JHU, see Figure 2. This rig was constructed through funding by the National Science Foundation, The Whiting School of Engineering at JHU, and the American Iron and Steel Institute. The upper load beam can apply compression (200 kips), bending moment (400 kip-ft), and shear (50 kips). The lower load beam can apply an independent bending moment. Using this testing rig a cold-formed steel component can be tested under any combination of axial and bending moment, as shown schematically in Figure 3.



(a) CAD model of MDOF testing rig

(b) MDOF testing rig in the JHU Structures Lab

Figure 2 MDOF Testing conducted by PI in the JHU Structures Lab (Yu and Schafer 2003)

(Upper (red) load beam can move vertically and/or horizontally and/or rotate about its long axis to apply axial load, and/or shear and/or bending moment to a specimen; the bottom load beam can rotate about its long axis so that any linear bending moment demand can be applied;, the rig can deliver 200 kips compression, 50 kips shear, and 400 kip-ft moment)

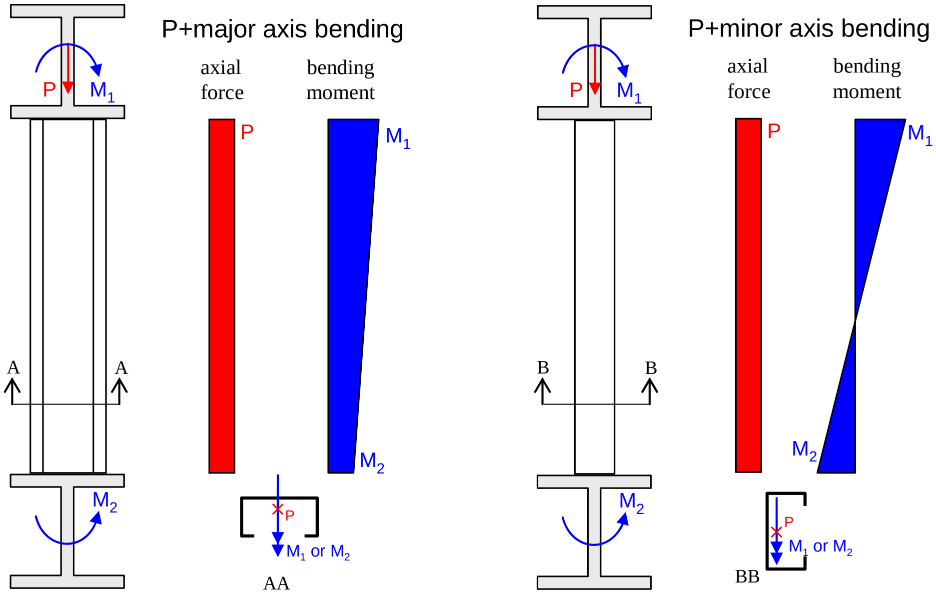


Figure 3 Schematic of a specimen in MDOF testing rig, oriented for major or minor-axis bending: showing applied axial force and one possible applied bending moment diagram (note any linear bending moment is possible).

The MDOF testing rig at JHU is unique and provides a means to experimentally investigate all relevant combination of axial load and bending moment, including moment gradients which are relevant to beam-columns. We will perform nonlinear FEA modeling of the rig and a typical test in the design phase so that we can explore and avoid the problem of local buckling failures occurring at the ends of the specimens. Design and fabrication of special end fixtures that are mounted into the MDOF testing rig are the primary addition to the capabilities of the MDOF testing rig anticipated in this project.

Why we need advanced computational work: currently we only accurately know the strength of an extremely limited number of beam-columns, and the number of significant variables is to large to perform the work by testing alone. To fully investigate the wide variety of cold-formed steel cross-sections under the numerous potential loading (any combination of P,M_x,M_y) end conditions (not just fix and pin, but real conditions like a stud screwed to track) and limit states (local, distortional, global – and potential interactions) requires an advanced analysis tool. Many of the theoretical challenges that need to be faced including: imperfection sensitivity, sections with large neutral-axis shift, limit state specific strength expressions under complicated loading, can all readily be investigated with nonlinear FEA, but are far more cumbersome and expensive to investigate in detail with an experimental program.

In line with previous success, shell element models of the members developed in ABAQUS using actual stress-strain coupons from the specimens, and probabilistically determined imperfections and residual stresses will be adequate for characterizing the distribution of ultimate strength and exploring the dominant failure mechanisms (Schafer and Peköz 1998). In addition to completing models of the sections tested herein, and parametric studies of other identified sections of interest it is also possible to explore several unique sections under eccentric load including rack sections with web and flange stiffeners recently tested as columns (Yang and Hancock 2003) and several unique beam sections (Rinchen 1998). Combined, the testing and nonlinear FE results will be used to determine appropriate strength expressions for local, distortional, and global buckling.

Details of the proposed plan for completing the research follow:

Industry survey on beam-columns

Survey industry (metal buildings, racks, metal studs, truss, etc.) for information on:

- sections commonly used as beam-columns,
- unusual sections (particularly un-symmetric sections, e.g., eave strut) used as beam-columns,
- end boundary conditions / connection practices for beam-columns,
- bracing details / connection practices for beam columns,
- current limitations, needs, areas of opportunity for more efficient beam-column design, and
- write a brief "summary of the practice" document to guide selection of specimens, development of testing protocols, and development of nonlinear FEA (ABAQUS) work.

Selection of specimen cross-sections

These tools will be used to aid in selecting the specimens:

- survey of industry,
- elastic stability analysis via finite strip analysis (CUFSM),
- strength estimate via a preliminary/approximate version of DSM for beam-columns, and
- strength estimate via current North American Specification.

To be determined are specimens that are important because of common use in the industry and specimens which have the potential to yield significantly different strength predictions than current AISI-S100 main Specification methods. A small class of specimens will be selected for experimentation and a much wider class for study by nonlinear FEA.

Selection of specimen length, boundary conditions, and loading protocols

In addition to the cross-section itself the specimen length, end boundary conditions, bracing, and loading (including eccentricity to produce axial + bending) all strongly influence the buckling failure being investigated. Using the same tools as in the selection of the specimen cross-sections, details will be determined to help select members and details that are

- dominated by local buckling for large range of axial + bending,
- dominated by distortional buckling for large range of axial + bending, and
- dominated by global buckling for large range of axial + bending.

In addition, members and details will be selected to specifically examine some of the peculiarities of beam-columns (as opposed to isolated beams, or columns) such as

- members which switch modes (e.g., from local to distortional) under different combinations of axial + bending,
- members which have the potential for significant interactions between local-global, local-distortional, distortional-global buckling modes,
- members which are predicted to have large neutral-axis shift under load, and
- members which may be path dependent, i.e. $P + M_x$ not the same as $M_x + P$ for strength.

Detailed nonlinear FEA will be needed to augment some of these investigations.

Nonlinear FEA of specimens

Detailed nonlinear finite element analysis (FEA) will be performed in ABAQUS to

- develop and verify members and details for the experimental program, and to
- perform large-scale parametric studies of a wider class of members and details.

FEA support for the experimental program will include

- investigating influence of end fixtures, and avoiding local buckling at the ends,
- insuring desired limit states (i.e., local, distortional, etc.) will be achieved by the testing rig,
- detailed comparison of local strain and deflection data,

- understanding imperfection sensitivity.

Goals of the larger parametric study are strongly related to the previous list of work for selection of a specimen cross-section, length, boundary conditions, and loading protocol and include

- examine members with large neutral axis shift,
- examine modal interactions,
- examine load path dependency to determine if experiments are warranted,
- quantify imperfection sensitivity,
- provide strength predictions for a wide class of members for use in developing design expressions.

Experimental program

The basic testing matrix (specimens, details, etc.) will de developed in the earlier stages of the work and verified with nonlinear FEA; however significant work remains in the experimental program consisting of

- building the end fixtures for the MDOF testing rig,

Actual testing includes

- specimen preparation,
- precision initial imperfection measurement,
- actual testing, including global load vs. deflection, and
- detailed deflection measurements, with limited strain measurements, followed by
- coupon tests, and
- post-processing and condensation of all results.

The testing provides numerous benefits including verification and validation opportunities for the nonlinear FEA models, and reliable strength predictions for the development of design provisions. Further, unique behavior (mode switching, mode interaction, large neutral axis shift, etc.) observed in the computational models can also be examined experimentally as needed.

Development of design provisions

The computational and experimental work will allow for the development of the design provisions. Specific tasks envisioned for generating the design provisions include:

- compilation of all computational and experimental results,
- develop limit state specific (i.e., local, global, etc.) strength equations, as a function of P, M_x, M_y from compiled results,
- develop methods for handling modal interactions as needed and observed,
- create a user-friendly numerical tool for beam-column stability (extending CUFSM),
- write provisions in specification language with commentary,
- write design examples illustrating common cases and highlighting significant differences, and
- prepare a specific industry impact statement for increased beam-column capacity predictions.

3. Impact on Industry

Properly modeling beam-column behavior will lead to an increase in predicted capacity. Currently we are throwing away potentially large reserve capacity in common cold-formed sections through the use of overly conservative linear interaction equations which are only truly accurate for fully effective doubly-symmetric sections, i.e., the hot-rolled I-beam. Appendix 1 provides a first glimpse of the potential reserve we are ignoring, shaded areas in Figure 4 and Figure 5 are regions where current methods are conservative. *For our most common sections, the C and Z, significant regions of loading exist where current methods fail us in that they are too conservative.*

A survey of industry practice, and a statement of industry impact are specifically included in the work to maximize the benefit and relevance of the proposed work to industry. The industry survey will be used to insure that beam-columns in heavy use in industry – whether a corner column in an in-line framed building, a rack post, an eave strut, or a truss chord are all considered in the developed work.

DSM needs the proposed work on beam-columns to fully provide a general means for strength prediction. DSM has the potential to have an enormous impact on industry; particularly product development. The ability to handle general cross-sections and high strength steel while still examining all relevant limit states opens the door to a new generation of cross-section optimization. Formation of cold-formed steel members is inherently flexible, but for years this has been largely ignored in industry, in part because design tools could not take advantage of highly optimized sections. DSM provides a means to a new end, one that the industry can use to fully utilize the strength and flexibility of steel members folded to shape.

4. Schedule and work plan

The proposed schedule for this project is for completion 36 months after contracts are issued and signed. The work is anticipated to be divided as detailed in Table 1.

Table 1 Work plan

	Year 1			Year 2			Year 3		
	Fa	Sp	Su	Fa	Sp	Su	Fa	Sp	Su
Industry survey on beam columns	🟦								
Selection of specimen cross-sections									
CUFSM analysis of all sections	🟦	🟦							
NAS strength prediction	🟦	🟦							
Selection of specimen details		🟦	🟦						
Nonlinear FEA of specimens									
supporting exp. program	🟦	🟦	🟦	🟦	🟦				
parametric studies			🟦	🟦	🟦	🟦	🟦	🟦	▨
Experimental program									
developing test matrix	🟦	🟦	🟦						
building rig and data acq.	🟦	🟦	🟦						
testing specimens		🟦	🟦	🟦	🟦	🟦	🟦	🟦	
Design provisions				▨	▨	▨	▨	▨	🟦

5. Work Product

Progress reports will be provided to AISI every 6 months at the AISI-COS meetings. A report will be provided upon completion of the project. Upon review and comments from the AISI a final report will be provided. A sample ballot including proposed specification provisions and commentary will be included in the final report. Test data and reports will be made available in electronic format to AISI and other researchers.

6. Budget

Beam-columns are a fundamental building block of cold-formed steel structures. Providing an entirely new, more accurate, and more efficient means for beam-column design and properly verifying and implementing this design is best completed with a multi-year effort. A proposed three year effort of $280,387 is summarized in Table 2 and completely broken down in Table 3. The summary in Table 2 allows AISI to examine the funding efforts required for the different portions of the proposed work. ***If only partial funding is available this budget and the statement of work should allow us to determine the most productive level of effort and then revise this proposal to match.***

Table 2 Summary Budget

BUDGET BREAKDOWN	Year 1	Year 2	Year 3	Total
Faculty	22,562	23,464	24,403	70,428
Graduate Student	48,510	50,542	52,660	151,712
Undergraduate Student	3,542	3,542	3,542	10,627
Travel/Dissemination	0	3,280	3,280	6,560
Experiment	16,200	8,200	8,200	32,600
Computation	6,820	820	820	8,460
	97,634	**89,848**	**92,905**	**280,387**

* Budget notes:

(1) Equipment costing greater than $5K is not subject to overhead

(2) The Department supports first-year graduate students, therefore the student on this project will be a second year student when joining the research (this provides a means to fund a student for 4 years with only 3 years worth of money).

(3) It is assumed that specimens will be donated for testing.

7. Facilities

Computer: Computing resources at Johns Hopkins University are nearly completely de-centralized. Computers in current use in the PI's research group were purchased through startup funds and other grants. All of my current graduate students have Dell workstation class Intel machines varying from 1 to 2 years old. In addition I have 1 high performance computing cluster used primarily for finite element analysis with ABAQUS; the cluster has 4 GB of memory per node and usese 64-bit Itanium chips (running Linux). Three computers with A/D boards and 1 laptop have also been purchased to support efforts in the lab. These resources will be available to support the research initiatives proposed herein. The proposed computational efforts will be aided by purchasing an additional node for the Linux cluster – this aids the CUFSM and ABAQUS analysis envisioned herein.

Laboratory: The Thin-walled Structures Lab in the Department of Civil Engineering is approximately 20 ft x 40 ft in plan and has a 20 ft. ceiling. The centerpiece of the lab is the MDOF testing rig described earlier in this proposal. This rig is capable of delivering compression (200 kips), shear (50 kips), and bending moments (+/- 400 kip-ft) to component or wall specimens. The lab also includes a testing rig with a 20kip hydraulic actuator currently configured for rotational restraint testing, and a 100 kip universal testing machine. The final two rigs are both controlled by the same MTS 407 controller. An adjoining laboratory of approximately the same size includes an additional 8,000 lbf hydraulic universal testing machine for dynamic testing, and a 10,000 lbf screw-driven universal testing machine – all available for use in this proposal. Laboratory sensors include, load cells, LVDTs, position transducers, extensometers, accelerometers and other sensors. Data acquisition capabilities include 3 computers with National Instruments A/D boards, 1 laptop with an A/D PCMCIA card, and a National Instruments SCXI system for conditioning and reading strain gauges, LVDTs, accelerometers and 20 other analog channels along with LabView. Miscellaneous supporting equipment for field instrumentation is also available. The PI has experience using this equipment in his research efforts to date.

Technician and admin. support: The Department has a full-time lab technician available to support the experimental testing proposed herein. The Department also has two full-time administrative staff which are available for help on an as-needed basis.

Table 3 Budget with detailed breakdown

3 Years - Start Date 09/01/08	**YEAR1**	**YEAR 2**	**YEAR 3**	
	09/1/08 - 08/31/09	09/1/09 - 08/31/10	09/01/10 - 08/31/11	Total
Faculty				
Ben Schafer (1 month)	10,383	10,798	11,230	32,411
Benefits (32.5%)	3,374	3,509	3,650	10,533
Total Direct Salary & Benefits	13,757	14,307	14,880	42,944
Total F&A Base	13,757	14,307	14,880	42,944
F&A (64%)	8,804	9,157	9,523	27,484
Total Faculty Costs	**22,562**	**23,464**	**24,403**	**70,428**
Graduate Student				
Graduate Student Salary (1 @12 months)	24,000	24,960	25,958	74,918
Tuition (for graduate students) **(no F&A)**	7,540	7,917	8,313	23,770
Health insurance (for graduate students) **(no F&A)**	1,610	1,691	1,775	5,076
Total Direct Graduate Student Costs	33,150	34,568	36,046	103,764
F&A Base	24,000	24,960	25,958	74,918
F&A (64%)	15,360	15,974	16,613	47,948
Total Graduate Student Costs	**48,510**	**50,542**	**52,660**	**151,712**
Undergraduate Student				
Salary (Summer: 9$/hr, 20hrs/wk, 3 mos.)	2,160	2,160	2,160	6,480
Total Direct Undergraduate Student Costs	2,160	2,160	2,160	6,480
F&A Base	2,160	2,160	2,160	6,480
F&A (64%)	1,382	1,382	1,382	4,147
Total Undergraduate Student Costs	**3,542**	**3,542**	**3,542**	**10,627**
Travel				
Dissemination of research results (conferences, etc.)	0	2,000	2,000	4,000
F&A Base	0	2,000	2,000	4,000
F&A (64%)	0	1,280	1,280	2,560
Total Travel	**0**	**3,280**	**3,280**	**6,560**
Experimental Support - Equipment & Supplies				
Testing Equipment **(no F&A)***[1]	8,000	0	0	8,000
Materials/Supplies (Testing)[2]	5,000	5,000	5,000	15,000
Total Direct Equipment & Supplies	13,000	5,000	5,000	23,000
F&A Base	5,000	5,000	5,000	15,000
F&A (64%)	3,200	3,200	3,200	9,600
Total Equipment & Supplies	**16,200**	**8,200**	**8,200**	**32,600**
Computational Support - Equipment & Supplies				
Computer **(no F&A)***	6,000	0	0	6,000
Software and licensing	500	500	500	1,500
Total Direct Equipment & Supplies	6,500	500	500	7,500
F&A Base	500	500	500	1,500
F&A (64%)	320	320	320	960
Total Equipment & Supplies	**6,820**	**820**	**820**	**8,460**
Total Direct	68,567	58,535	60,586	187,688
Total F&A base	45,417	48,927	50,498	144,842
Total F&A	29,067	31,313	32,319	92,699
Total Budget	97,634	89,848	92,905	280,387
Total All Major Items	**97,634**	**89,848**	**92,905**	**280,387**

* equipment: single item costing >$5K = no overhead

[1] a custom jig will be manufactured for use in the MDOF testing rig already constructed at JHU

[2] as typical, it is assumed that specimens will be donated; however, end fixtures will need to be welded/attached to specimens

8. Personnel

In addition to the principal investigator one graduate student and one part-time undergraduate student is requested for supporting the research proposed herein. As discussed in the statement of work the research is envisioned in 3 parts: conceptual, computational, and experimental. The focus of the principal investigator's (PI's) efforts will be the conceptual work, including development of design provisions, development of testing protocols, and verification and validation of the computational models employed. In addition, the PI will provide training and advising for one graduate student who will do the bulk of the proposed computational and experimental work. The Department of Civil Engineering supports all first-year graduate students, therefore the student selected for this work would not be brought on to the project until their second year of research. This insures far greater productivity for the research and is a form of cost sharing that the Department extends to all funded research projects. A three year project would allow the graduate student to completely focus their efforts on this work and provide funding towards a Ph.D. A one page resume of the PI is attached.

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Appendix 1: Preliminary Exploratory Work

The combinations of P,M_x,M_z that cause first yield in the cross-section ($|f_{max}|=f_y$) are the most fundamental quantities to the strength prediction of a beam-column. A linear interaction equation assumes that first yield of a fully effective section may be captured via:

$$\frac{P}{P_{yield}}+\frac{M_x}{M_{x-yield}}+\frac{M_z}{M_{z-yield}}=1.0 \qquad \text{(A1)}$$

where:

P axial demand when combined with M_x and M_z that cause first yield
M_x bending demand about the *x*-axis that combined with P and M_z cause first yield
M_z bending demand about the *z*-axis that combined with P and M_x cause first yield
P_{yield} is the isolated axial load that causes first yield in the cross-section ($A_g f_y$)
$M_{x\text{-}yield}$ is the isolated bending moment about the *x*-axis that causes first yield ($S_{gx} f_y$)
$M_{z\text{-}yield}$ is the isolated bending moment about the *z*-axis that causes first yield ($S_{gz} f_y$)

Figure 4 was generated to explicitly demonstrate the conservative nature of linear interaction equations such as Eq. A1, even for predicting first yield in a fully effective cross-section. Figure 4 also demonstrates that interaction equations are cross-section dependent, and no one expression will work. For each of the 5 sections analyzed in Figure 4: I, T, C, Z, and an un-symmetric angle member, the combination of loading causing first yield in the cross-section is illustrated for: axial load + major-axis bending, axial load + minor-axis bending, and bi-axial bending. In Figure 4 the actual P,M_x,M_z that causes first yield in the section is denoted with a solid line, the linear interaction equation (Eq. A1) is denoted with a dashed line – the difference between the two quantities is shaded. The extent of shading is related to the overly conservative nature of the linear interaction equation.

As illustrated in Figure 4, Eq. A1 is exact for first yield of fully effective doubly-symmetric sections, such as an I. Singly-symmetric sections, such as the T or C are exact when bent about their axis of symmetry, but conservative otherwise. The magnitude of the conservative error in the linear interaction equation, denoted by the shading in the figure can be quite large for common singly-symmetric sections, but is dependent on the specifics of the cross-section. Point-symmetric sections, such as the Z provided in Figure 4 (here in restrained bending about the x and z axis, consistent with a laterally braced Z) demonstrate the absolute futility of the universal application of the linear interaction equation which works exactly for axial-moment interaction but is absurdly conservative for biaxial bending. In the general case of an un-symmetric section the linear interaction equation for first yield is always conservative – with the error completely cross-section dependent. Linear interaction equations such as A1, or equivalently the Eq.'s in C5.2.1 and C5.2.2 in the NAS, are only exact – for fully effective sections – when bending occurs about an axis of symmetry.

First yield is a key limiting quantity for capacity (strength) prediction; however in thin-walled cold-formed steel members stability limit states related to local, distortional, or global buckling (and their potential interactions) play an important role. In current design approaches, whether effective width approaches of the main NAS or the DSM approach of the new Appendix 1, the strength of a beam-column is determined by finding the isolated beam strength and isolated column strength and applying an interaction equation. The isolated beam and column strengths are a function of the instability under consideration (local, distortional, global). The combination of these strength in the linear interaction equation presumes that stability limit states also follow a linear interaction, thus the combinations of P^*,M^*_x,M^*_z that cause buckling may be defined via:

$$\frac{P^*}{P_{cr}} + \frac{M_z^*}{M_{xcr}} + \frac{M_z^*}{M_{zcr}} = 1.0 \qquad \text{(A2)}$$

where:

P^* axial demand when combined with M^*_x and M^*_z that cause buckling
M^*_x bending demand about the x-axis that combined with P^* and M^*_z cause buckling
M^*_z bending demand about the z-axis that combined with P^* and M^*_x cause buckling
P_{cr} is the isolated axial load that causes buckling
M_{xcr} is the isolated bending moment about the x-axis that causes buckling
M_{zcr} is the isolated bending moment about the z-axis that causes buckling

Figure 5, similar to Figure 4, provides the actual interaction results for local bucking and compares them to the linear interaction assumption of Eq. A2. For stability, regardless of the cross-section, linear interaction equations such as Eq. A2 are not exact. The exact solution for the interaction is highly cross-section dependent. In Figure 5 the actual combination of P^*,M^*_x,M^*_z that causes elastic local buckling in the section is denoted with a solid line, the linear interaction equation (Eq. A2) is denoted with a dashed line – the difference between the two quantities is shaded. The extent of shading is related to the overly conservative nature of the linear interaction equation.

Similar to prediction of first yielding in the cross-section, it is conservative to use the isolated column and beam (buckling) values, but it is not exact. Stability depends on the details of the cross-section and the actual stress distribution on the section – ignoring this fact may lead to significantly conservative predictions of the beam-column strength.

The examples of Figure 5 indicate that the error in Eq. A2 is not too great for most sections in axial + bending – but for biaxial bending the linear interaction assumption appears nearly always significantly conservative. One case where the assumption of a linear interaction equation seems particularly troublesome is singly-symmetric sections when bent about their un-symmetric axis. For example, the behavior of a lipped channel under axial load + minor-axis bending is strongly dependent on the specifics of the applied stress.

While distortional buckling and global buckling further complicate matters for strength prediction, we may conclude for these other stability limit states – that they too cannot be directly captured by the assumption of a linear interaction equation.

Figure 4 and Figure 5 serve to demonstrate that direct analysis of the stress on a beam-column both for prediction of yielding and buckling provides more accurate solutions and avoids the excessively conservative predictions of our current design approaches employing a single linear interaction equation. At the same time, the figures also show that a linear interaction diagram may continue to provide a quick and conservative prediction, that may be useful for preliminary or non-essential design.

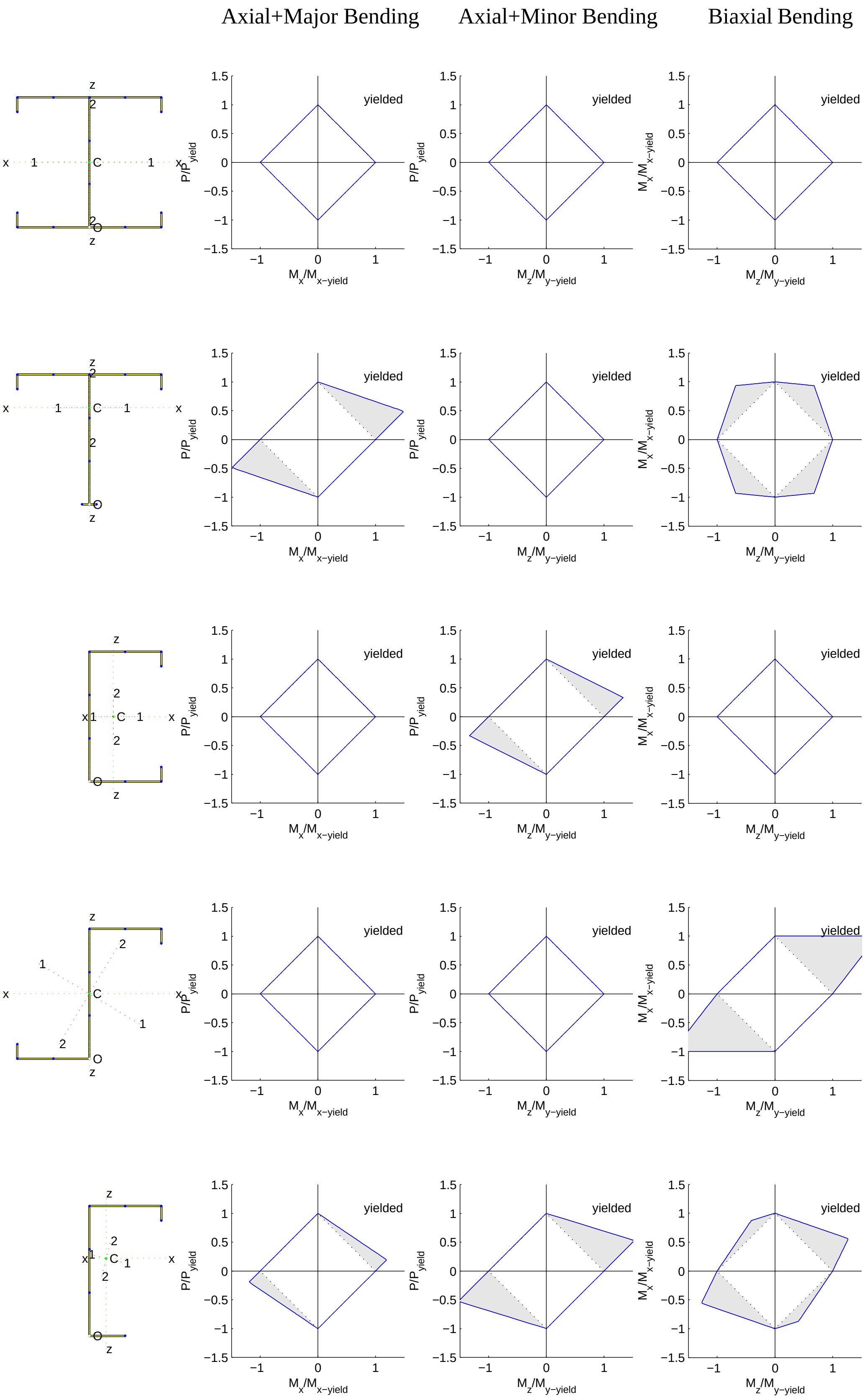
Axial+Major Bending Axial+Minor Bending Biaxial Bending

Figure 4 Interaction diagrams for first yield of fully effective sections
(Shaded areas indicate difference between actual first yield, solid line, and a linear interaction equation, dashed line. Calculations are performed assuming restrained bending about x and z axes. The C section has a web height of 9 in., flange width of 5 in., lip length of 1 in., and t=0.10 in., all others drawn to scale.)

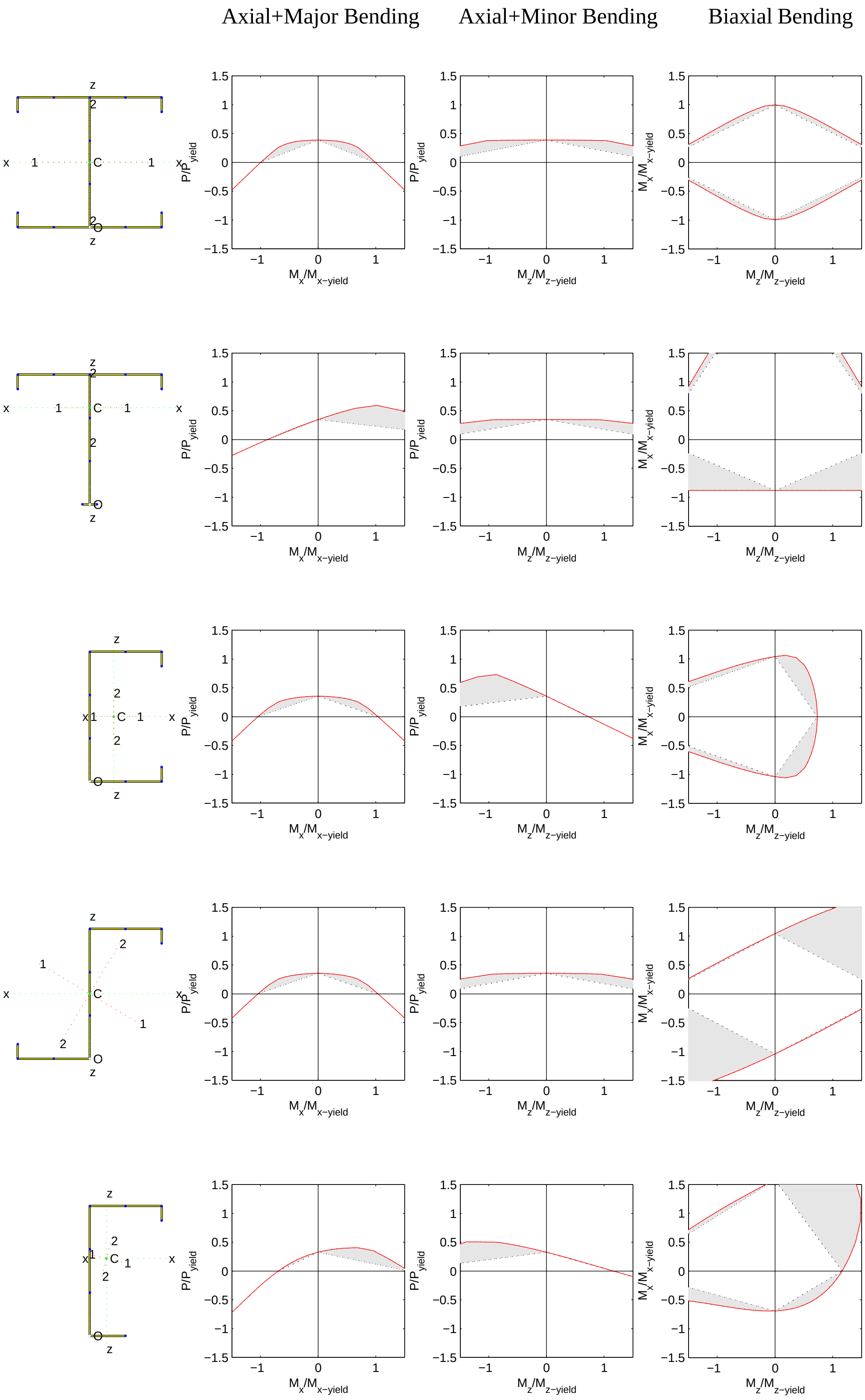

Figure 5 Interaction diagrams for elastic local buckling

(Shaded areas indicate difference between actual elastic buckling, solid line, and a linear interaction equation, dashed line. Calculations are performed assuming restrained bending about x and z axes. The C section has a web height of 9 in., flange width of 5 in., lip length of 1 in., and t=0.10 in., all others drawn to scale.)

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HONORS

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Teaching	*Robert S. Pond, Sr. Excellence in Teaching Award (2004)*
Service	*Dunn Family Award – from the JHU Student Council (2004)*

PROFESSIONAL

Associate Professor	*The Johns Hopkins University, Baltimore, MD* Department of Civil Engineering. (July 2006 – Present)

TEACHING

Assoc. Prof.	*The Johns Hopkins University* (2000 – Present) What is Engineering?, Perspectives on the Evolution of Structures, Structural Analysis, Steel Structures, Structural Reliability, Structural Stability
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SERVICE & ACTIVITIES

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